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CORRELATION ANALYSIS OF KINETIC ENERGY OF BALLS AND COAL LOAD FOR BALL MILLS

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Abstract. *To improve the performance of the coal load detection based on the kinetic energy of the balls in a ball mill, the variation of the boiler operation parameters under the normal operating condition is analyzed by the polynomial fitting and information fusion model. A Discrete Element Method (DEM) experiment for ball kinematics based on the coal load is proposed. The operating process for a ball mill and the ball motion, as influenced by the coal quality and the coal load, is analyzed carefully. The relationship between the operation parameters, the kinetic energy of balls and the coal load is obtained. Origin and Matlab are utilized to draw the variation law between the real-time kinetic energy of balls, the friction energy consumption, the strain energy and the mill total work with increasing coal loads in the projectile and cascading motion states. Meanwhile, a balanced adjacent degree method is proposed to verify the considerable effect of the kinetic energy of balls on the coal load. The results indicate that a coal load control method based on the kinetic energy of balls is therefore feasible for the optimized operation of a coal pulverizing system.*
Keywords: Coal load, Kinetic energy of balls, DEM, Law of motion, Control method

1. **Introduction.** Ball mills, which crush and grind coal to a target size for the supply for boiler combustion, are important auxiliary equipment in thermal power plants. Their coal grinding efficiency is closely related to the economy of the power plant, as discussed by Gupta and Sharma [1]. The control requirement for a pulverizing system is to guarantee that the coal load in the ball mill is close to the optimum level. Therefore, accurately measuring and controlling the coal load of a ball mill are the key problems and technical difficulties in thermal power plants. Currently, the various detection methods include the differential pressure method, the vibration method, the noise method, the ultrasonic method, the power method and different combinations of these methods. In the differential pressure method, the coal load is expressed in terms of the pressure difference between the inflow and outflow of a ball mill, and the measuring precision is finite and determined by the air rate. The fundamentals of vibration method are to analyze the relationship between the vibration strength of the system and the coal load at a constant rotational speed of the ball mill. However, this method has poor linearity and low accuracy. In detecting the coal load, the noise method utilizes ball mill noise, which has poor anti-interference and large deviations due to the effect of environmental noise on the audio signals. The ultrasonic inspection method realizes coal detection by building relations in the sending-receiving interval between the ultrasonic sensor and the interface. The shortcomings of this method are a high system cost, demanding environmental requirements and the lack of stability and reliability. In the power method, material levels are detected by the power transformation rule of the coal load. Nevertheless, the sensitivity of this

method needs to be improved, and it may be difficult to estimate the coal load when power decreases. The above mentioned methods cannot truthfully reflect the coal load in ball mills because they have many limitations and low accuracies [2,3].

The motion of the ball mill's medium can directly influence the power consumption of grinding and is associated with the grinding mechanism [4,5], Lu et al. [6] and Davis [7] studied the projectile motion in ball mills and established the ball's motion equations by experiments, and they developed a systematic theory for grinding the coal. Ying [8] studied the influence of the mill's rotation rate, the ball filling ratio and many other factors on balls' motion. Afterwards, many domestic and overseas scholars performed experiments and developed medium movement form theories, such as the two-phase movement theory [9-11]. Although there is already a considerable amount of research on the medium's motion track and how the mill's working parameters influence the medium's motion in different subareas, there are only a few studies on using the grinding medium as a control parameter.

To improve the performance of the coal load control method, the balls' kinetic energy is utilized to detect and control the coal load in this paper, which avoids the influence of other factors and enhances the accuracy of coal detection. Meanwhile, this work establishes the polynomial fitting and information fusion model between the multiple operation parameters of the boiler and the coal load. A Discrete Element Method (DEM) is used to analyze the kinematics of the balls under the influence of the coal load. A balanced adjacent degree method further confirms that the balls' kinetic energy can reflect the coal load more accurately than other operation parameters of boiler. In comparison to these existing coal load control methods, this analysis approach relates ball motion and coal load together, and it can realize a better coal load control method based on the balls' kinetic energy and improve the coal grinding efficiency.

There are six parts in this paper. The first part is the summary of related work, the significance and motivation of the paper. The second part is a balanced adjacent degree method for the variation of operation parameters of the boiler to establish experimental model. The third part presents the preconditions, assumptions and parameters of PFC3D model for ball motion under the influence of coal quality and coal load. The fourth part analyzes the correlation model of operation parameters, balls' kinetic energy and coal load. Experiments and result analysis and correlation among parameters are in the fifth part which shows the effectiveness of the novel coal load control method by comparing kinetic energy values. The major findings and innovation of the study are summarized finally in the conclusion.

2. **Operation Parameters and Methods.** Boiler operation parameters influence other parameters or even the whole boiler operating condition. By on-line monitoring the multiple operation parameters, the correlation degree between the coal load of pulverizing system and the boiler operation parameters is analyzed, which is of great importance to supervise the security and economy of the boiler. However, not all operation parameters have a significant impact on the coal load. According to the principle of the sensitivity, the accuracy, and a minimum dimension, we can select appropriate variables to improve the accuracy of the correlation model by using the method of mechanism analysis [12]. In addition, the data on the parameter variation are collected in the field when the boiler operates.

The correlative degree combined with the balance degree is utilized to analyze the multiple variables of the boiler, and verify that the balls' kinetic energy is more applicable than other preselected variables for the control of the coal load in a ball mill. Correlative degree is a measure of the correlation degree of the factor variation trends between two systems with the increase of time or other variables. We judge the connect-degree between the reference data sequence and the comparison data sequence according to the geometrical relation and similarity of the generated data curves. The more approximate the curve trends are, the bigger the correlation degree of the corresponding sequence is, and vice versa.

The reference data sequence reflects the behavioral characteristics of system,

$$x_i(f_k) = \{x_i(f_1), x_i(f_2), \ldots, x_i(f_n)\} \tag{1}$$

the comparison data sequence affects the factors of system performance,

$$x_j(f_k) = \{x_j(f_1), x_j(f_2), \ldots, x_j(f_n)\} \tag{2}$$

the absolute difference between $x_i(f_k)$ and $x_j(f_k)$ is:

$$|x_i(f_k) - x_j(f_k)| = \Delta_{ij}(f_k) \tag{3}$$

and the correlation coefficient of $x_i(f_k)$ and $x_j(f_k)$ is:

$$\xi_{ij}(f_k) = \frac{\Delta_{\min} + \Delta_{\max}}{\Delta_{ij}(f_k) + \Delta_{\max}\eta} \tag{4}$$

Among all sequences, $\Delta_{\max}$ and $\Delta_{\min}$ are the maximum and minimum absolute difference, generally with $\Delta_{\min} = 0$. The distinguishing coefficient is $\eta \in (0, 1)$. The correlation degree between the reference data sequence and the comparison data sequence is calculated by the following formula [13]:

$$\gamma_{ij} = \frac{1}{n}\sum_{k=1}^{n} \xi_{ij}(f_k), \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, l; \quad k = 1, 2, \ldots, n \tag{5}$$

To reduce the association tendency of local points, the balance degree is further adopted to measure and compare the correlation degree of the data sequence's correlation coefficient series [14,15]. Supposing the correlation coefficient series of the jth comparison data sequence and the ith reference data sequence is $R_{ij} = \{\gamma(x_i(k), x_j(k))/k = 1, 2, \ldots, n\}$, then the correlation coefficient distribution map is $Map : R_{ij} \to P_{ij}$,

$$p_{ij}(k) = \gamma(x_i(k), x_j(k)) \Bigg/ \sum_{k=1}^{n} \gamma(x_i(k), x_j(k)) \tag{6}$$

where $k = 1, 2, \ldots, n$, $p_{ij} \in P_{ij}$. We can define the following equation based on Equation (6):

$$H_{\otimes}(R_{ij}) = -\sum_{k=1}^{n} p_{ij}(k) \ln p_{ij}(k) \tag{7}$$

The above equation is the correlation coefficient's entropy of the jth comparison data sequence and the ith reference data sequence, and the balance degree is (8):

$$B(R_{ij}) = H_{\otimes}(R_{ij})/H_m(R_{ij}) \tag{8}$$

where $H_m(R_{ij})$ is the largest entropy in the jth comparison data sequence, and it is expressed as $L_n^{(\text{sequence number})}$. Thus, the balanced adjacent degree is:

$$B_a(X_i, X_j) = B(R_{ij}) \times \gamma(X_i, X_j) \tag{9}$$

where $X_i = \{x_i(k), k = 1, 2, \ldots, n\}$, $X_j = \{x_j(k), k = 1, 2, \ldots, n\}$.

The correlation degree between each comparison data sequence and reference data sequence is ordered by the balance adjacent degree. Finally, we can determine the relationship between the comparison parameter and the reference parameter, and obtain the effective theory, which is based on parameters' physical significance.

3. **DEM Experiment.** Since DEM is a numerical computation method for discontinuous medium mechanics, and is used for solving and analyzing granular material's equations of motion and kinetic parameters [16-18]. Fundamental assumptions are very important prerequisites for DEM analysis. The fundamental assumptions of this study are as follows.

1) The particle unit is regarded as a rigid body and a sphere.

2) Contacts happen over a tiny area, which is a point contact. There is special joint strength in the contact place.

3) The contact is a flexible contact. It allows a certain overlap, which is tiny in comparison with the particle size in the contact area, and it relates to contact force.

4) The time step is small. Any unit disturbance from indirect contact should be avoided, and the velocity as well as the accelerated velocity of any time step is constant.

DEM is used to simulate the ball mill when the working parameter configuration is quantitative optimized [19,20], and it records the real-time simulated experimental data of the balls' kinetic energy by directly observing the ball motion when the mill's coal load is different. The DEM experiment model analyzes the ball kinematics with increasing coal loads under different parameter conditions.

3.1. **Material and apparatus.** Because of the high-speed, discreteness and randomness of the medium's motion and the uncertainty of the coal load, it is difficult for the traditional methods to analyze the motion and grinding mechanisms of the medium with variation of the mill's coal load. Therefore, the simulation of a ball mill catches more and more attention from industry insiders. The motion states of the grinding medium for ball mills are greatly influenced by the working parameters. There is a high grinding efficiency for ball mills with the appropriate structure parameter, operating parameter and medium parameter configuration. To improve the simulation results of the DEM model, a ball mill is modelled by a cylinder with special material characteristics according to the ball mill's performance in the structure parameter configuration. The standard dimensions are Ø0.4 m × 1.2 m with certain rough wearable steel liner plates fixed inside the wall. The cylinder's boundary is 1/6 of the initial length due to cutting the axle. In the medium parameter configuration, balls and the coal inside the mill are modelled by spherical discrete elements of certain material characteristics and size. The balls' diameter is $D_b = 0.03$ m, and their bulk density is $\rho_{gq} = 4.9$ t/m^3. The coal particles' radiuses are $R_m = 3, 4, 5, 6, 7, 8$ mm, and their bulk density is $\rho_m = 0.75$ t/m^3. In the operating parameter configuration, the rotation rate Φ, the ratio of the working speed to the critical speed of the mill, is selected as $\Phi = 80\%$. In a particle and contact model, a "ball-ball" contact and a "ball-wall" contact are affected by the contact force. The parameters with the most influence on the contact force are the stiffness, the damping and the friction factor. The parameter values for the model used in this simulation experiment are given in Table 1. The stiffness represents the stress resistance of balls to elastic deformation, the friction factor affects the power consumption of ball mills, and the damping main influences the accumulation process and the course of energy dissipation. According to the estimate method for experiments, a proper simulating variation range for the mill's parameters given a quantitative overlap coefficient, a Poisson ratio and a coefficient of restitution are considered [21]. The optimized configuration of the above model parameters is obtained by adjusting the associated performance parameters of the materials, and the ball mill model is established by setting the initial parameters, which include viscous damping, a cylindrical shape, and spiral walls.

3.2. **PFC3D model.** PFC3D is used to simulate the motion and interaction between the balls and the coal by DEM [22-24]. The balls inside the mill are discontinuous, and the PFC3D model, which is based on a command driving mode, is good at processing

TABLE 1. Model parameters

model parameters	parameter values
friction factor (ball-ball)	0.142
normal stiffness (ball-ball)/(N/m)	2.0×10^5
shear stiffness (ball-ball)/(N/m)	2.0×10^5
friction factor (ball-wall)	0.189
normal stiffness (ball-wall)/(N/m)	4.0×10^5
shear stiffness (ball-wall)/(N/m)	3.0×10^5
ball's density/(kg/m^3)	7.8×10^3
normal damping	0.3
tangential damping	0.3

discontinuous problems because it can demonstrate ball motion in a natural way, as discussed by Geng et al. [25]. The PFC3D model uses an explicit difference algorithm and the theory of discrete element simulation to calculate the balls' kinetic energy with increasing coal loads.

The contact patterns in the PFC3D model include a "ball-ball" contact and a "ball-wall" contact. Supposing that we can simulate the three-dimensional motion of a particle system by setting the contact model of the balls and the coal, the boundary conditions, and the force as well as particle properties, there exists an optimum value Ψ_{zj} in the ball filling ratio that corresponds to a rotation rate Φ [26], that is:

$$\Psi_{zj} = \frac{0.12}{\Phi^{1.75}} \tag{10}$$

and then the optimum ball charge is:

$$G = \frac{1}{4}\rho_{gq}\pi D^2 L \Psi_{zj} \tag{11}$$

The approximation calculation equation for the number of the ball is [27]:

$$N \approx 1.2\frac{\psi\pi D^2 L}{4D_b^3} \tag{12}$$

where L is the mill's effective length, D is the inner diameter of mill, and Ψ is the ball filling ratio of ball mill. After the calculation, the number of simulated balls for diameters of 0.03 m is $N_{0.03} = 200$, respectively. With increasing coal loads, the variation tendency of the kinetic energy, the strain energy, the friction energy consumption and the mill's total work was analyzed based on these two parameter conditions.

4. **Operation Parameter and Coal Load Correlation Model.** Through mechanism analysis, the preselected variables would focus on the coal load, the active power, the feed water flow, the air preheater inlet flue gas oxygen content, the furnace negative pressure, the primary air flow, the supply air rate and the throttle pressure in thermal power plants. Figure 1 shows the real-time data about the preselected variables aforementioned from Baiyinhua Jinshan Power Generation Co., Ltd.

According to Formulas (6)-(9), the balanced adjacent degree between the coal load as the reference data sequence and other parameters as the comparison data sequences is calculated, as shown in Table 2. The results show that the balanced adjacent degree values between the air preheater inlet flue gas oxygen content, the furnace negative pressure and the coal load are lower than 0.6, so there is no correlation between them. Eventually, the active power, the feed water flow, the primary air flow, the supply air rate and the

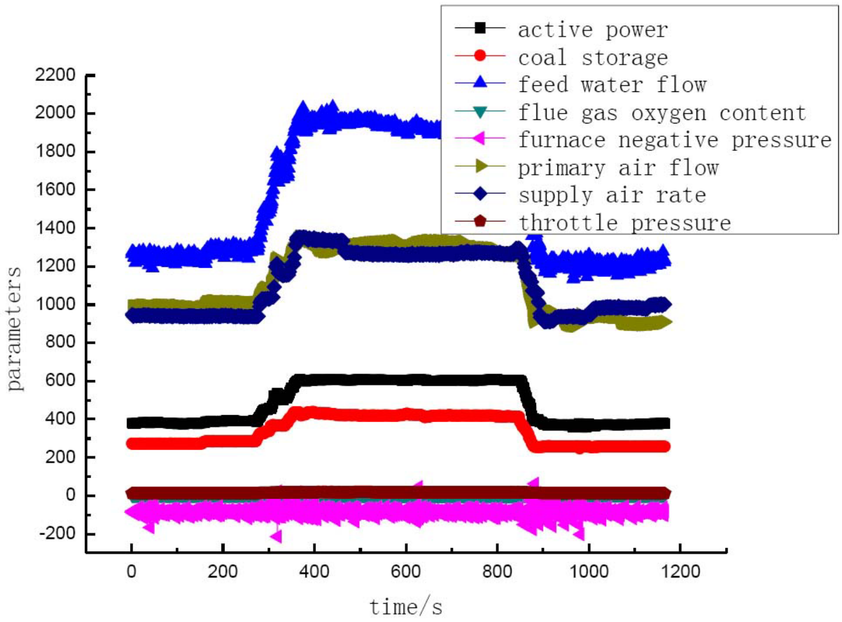


Figure 1. Scatter diagram of parameter data

Table 2. Balanced adjacent degree between operation parameters and coal load

parameters	active power	feed water flow	flue gas oxygen content	furnace negative pressure	primary air flow	supply air rate	throttle pressure
$B_a(X_i, X_j)$	0.8788	0.9149	0.5086	0.5356	0.7471	0.7184	0.7693

throttle pressure are selected as the auxiliary variables to establish the polynomial fitting and information fusion model.

4.1. **Operation parameter and coal load polynomial fitting model.** To examine the influence degree of boiler operation parameters on the coal load, the polynomial fitting model is established. Table 3 demonstrates the fitting function relation between the operation parameters and the coal load. It is obvious that the fitting degree of parameters is higher than 93% with a significant effect; besides, the error is lower than 5%.

4.2. **Operation parameter and coal load information fusion model.** The multi-parameter information fusion model is established for operation parameters as the auxiliary variables. The error, the residual and the confidence level are analyzed from the viewpoint of statistics. The influence degree of the coal load resulting from multiple parameters operating simultaneously is researched. The results of statistical analysis are shown in Table 4 and Table 5.

In Table 4, the fitting degree of the information fusion model is 0.9904, which is higher than that of the polynomial fitting model. In addition, the error is 0.0146, which is lower than that of the polynomial fitting model. Consequently, compared with an individual operation parameter, multiple operation parameters indeed have more influence on the coal load. From the statistic results in Table 5, we know that the confidence level of the regression equation model is approximately equal to 1 and F-value is 24009. Considering the parametric variance, the simulation accuracy is higher, and the coefficient estimates

Table 3. Analysis results of polynomial fitting model

parameters		active power	feed water flow	primary air flow	supply air rate	throttle pressure
expression	quadratic	–	–	–	–	2.4451
	linear	0.6790	0.2190	0.4312	0.4495	–35.8744
	constant	10.8250	–4.1747	–145.6470	–158.6134	348.6837
fitting degree		0.9811	0.9816	0.9786	0.9334	0.9648
error		0.0226	0.0215	0.0289	0.0491	0.0329

Table 4. Analysis results of information fusion model

parameters	constant	active power	feed water flow	primary air flow	supply air rate	throttle pressure
expression of b	–2.7191	0.5576	0.3882	0.4044	0.1047	–0.4469
fitting degree			0.9904			
error			0.0146			

Table 5. Statistical test results of parameter estimation

parameter	confidence level	F statistic	corresponding P	estimation of variance
stats (b)	1	24009	0	54

Table 6. Relation model of balls' kinetic energy and coal load

model	quadratic	linear	constant
expression	0	–0.0057	12.4336
fitting degree		1	
error		0.0036	

are more correct than the situation of polynomial fitting model. P-value is low, approximately equal to 0, and the regression equation model is successfully set up. Because the information fusion model gets small error, the result shows that the balanced adjacent degree method has a great accuracy.

The residual plot, shown in Figure 2, demonstrates that the experimental data have high reliability within the range of 95% confidence interval because of few abnormal experimental points. However, the residual value is approximately 0.0022, and it is bigger than 0.001 which is the typical value of residual in single precision. The results indicate that the regression model's performance is not very perfect.

Table 6 represents the polynomial fitting model of the balls' kinetic energy and the coal load. The fitting degree of the relation curve is close to 1. The error is 0.36%, which is much smaller than the error of the multi-parameter model (1.46%). It is shown that the multiple operation parameters fusion model can reflect the state of the ball mill coal loads. The correlation degree between the balls' kinetic energy and the coal load is great in comparison with the effect of the fusion model. The kinetic energy of ball motion can have more explanatory power to the coal load than the other operation parameters. Results show that the balls' kinetic energy is therefore applicable for control of the coal load in ball mill.

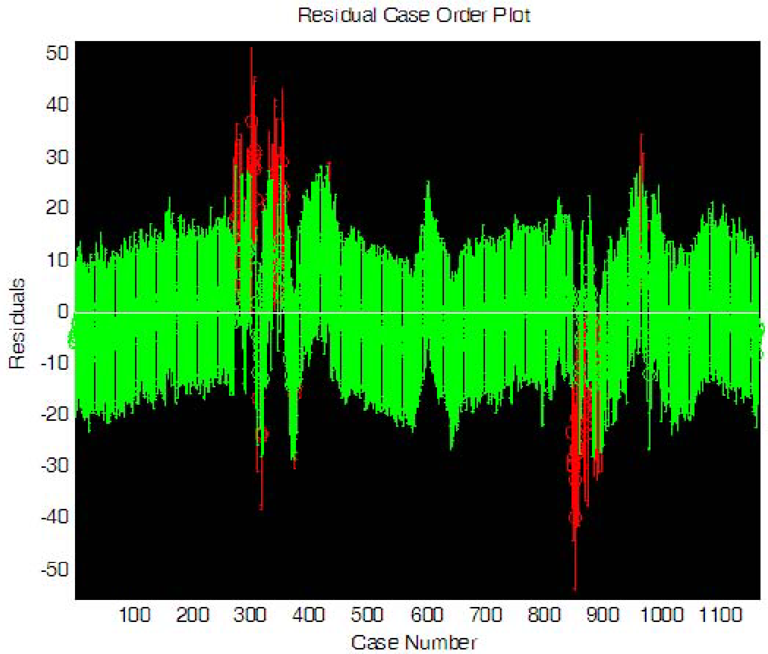


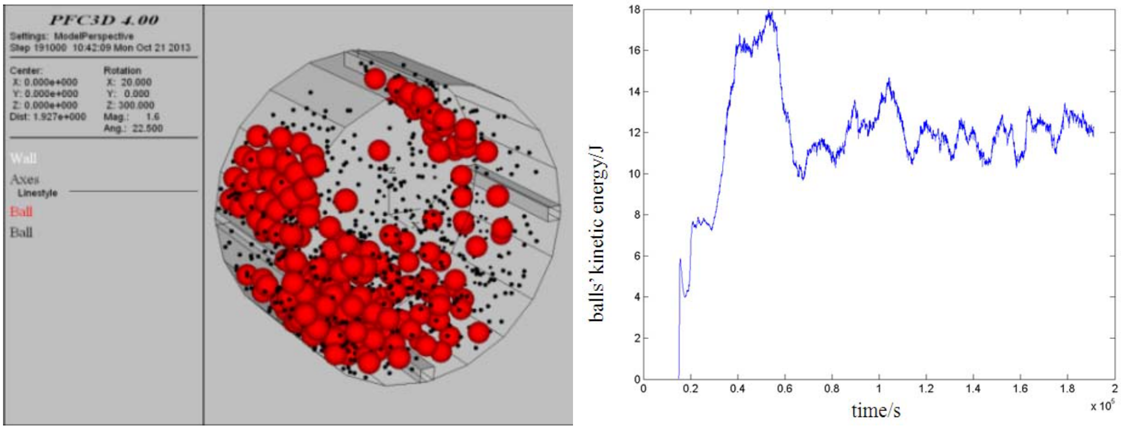
FIGURE 2. Residual plot of information fusion model

5. **Results and Discussion.** The force and boundary conditions for the balls and the coal are limited, and the accumulation of particles appears naturally. The kinetic energy, the friction energy consumption and the mill's total work for any location and size are conveniently determined in the ball and coal accumulation system. A three-dimensional image of the balls and the coal can be directly generated. PFC3D tracks every particle's motion periodically and repeatedly, thus obtaining the motion of the overall granular mixtures.

Based on the PFC3D model, the initial values of the coal load are an arithmetic progression whose $a(1) = 100$, $d = 200$ and $a(7) = 1300$. The mill rotates uniformly in 5.6 rpms. The simulation experimental results for 4 revolutions of the cylinder are as follows.

5.1. **Effects of $D_b = 0.03$ m and $N_{0.03} = 200$.** Figure 3(a) indicates the balls' distribution and motion of the mill when it is running in a steady state after adding coal particles of $R_m = 3$ mm and $N_m = 700$. Figure 3(b) illustrates the real-time variation curve of the balls' kinetic energy after the rotation of the cylinder, and it concludes that the balls' kinetic energy reaches the obvious peak value when the projectile ball and the coal come to a certain value. Moreover, there exists a regular fluctuation of kinetic energy with the circulating rotation of the cylinder.

With increasing coal loads, the maximum and average values of the balls' real-time kinetic energy, the friction energy consumption and the mill's total work are shown in Table 7 and Figure 4, where K_{pj0}/W_{w0} represents the average value of the balls' kinetic energy as a percentage of the mill's total work when the mill rotates 4 revolutions without coal. In Table 7, the balls' work on the coal particles with different diameters is first increasing and then decreasing as the coal load increases. When $R_m = 3$ mm and $N_m = 700$, the balls' kinetic energy accounts for 9.2831% of the mill's total work, which is higher than the situation when there is no coal (6.4537%). That is, $K_{pj}/W_w - K_{pj0}/W_{w0} = 2.8294\%$. When $R_m \geq 6$ mm, the increase of kinetic energy of the ball load becomes smaller and smaller as the coal load increases. When $R_m = 8$ mm, the projectile motion



(a) Simulation model of ball motion (b) Real-time kinetic energy of balls

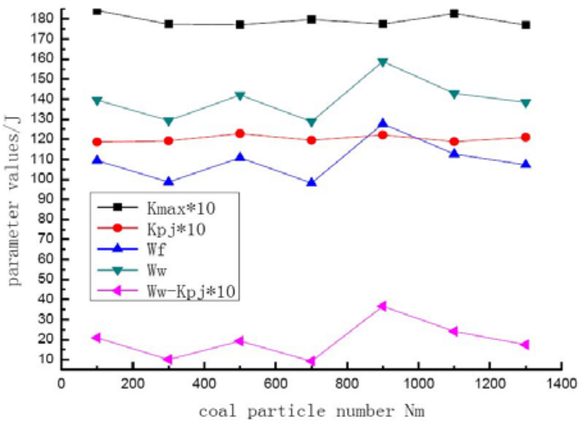
FIGURE 3. PFC3D effect chart of $D_b = 0.03$ m and $N_{0.03} = 200$

disappears, and the motion of the balls is mainly grinding and squeezing. Therefore, different ball mills and parameters are suitable for a limited range of coal diameters.

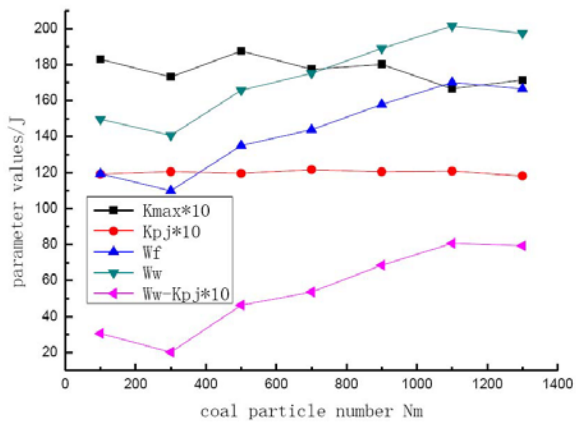
The maximum and average values of the balls' kinetic energy for different coal particles' radiuses, friction energy consumption and the mill's total work with increasing coal loads are clearly demonstrated in Figure 4. To reflect the variation of the curve in Figure 4, the maximum and average values of the balls are amplified by a factor of ten. The pink curve, shown in Figure 4, represents the difference between the mill's total work and ten times the average value of the balls' kinetic energy ($W_w - K_{pj} * 10$). As a result, the variation of the friction energy consumption and the variation of the mill's total work are fundamentally the same. After $W_w - K_{pj} * 10$ is larger than its minimum, it increases gradually and the mill's total work rises while the balls' kinetic energy remains almost the same. The minimum of the curve corresponds to the optimal coal load, which further indicates that when the coal load exceeds a certain value, both the mill's useful work and the use ratio of the balls' kinetic energy decrease. Therefore, the real-time kinetic energy of the ball motion closely relates to the coal load and the mill's operational efficiency.

In the comparison between Table 7 and Figure 4, we can learn that the increasing range of the balls' kinetic energy with different coal particles' radiuses and coal loads reduces. However, when $R_m \leq 6$ mm, the balls' kinetic energy increases in the beginning and then decreases with increasing coal loads. The larger the coal particle's radius is, the less the optimal coal load corresponds to the maximum of the balls' kinetic energy. $W_w - K_{pj} * 10$ increases with increasing coal loads but has a minimum point. Therefore, the motion space of balls inside the mill is limited. When the coal load exceeds the optimum value, the balls' impact strength gradually decreases, and grinding plays a leading role. Because it is influenced by the ball's diameter and the coal particle's radius, the optimal coal load possesses different functional values.

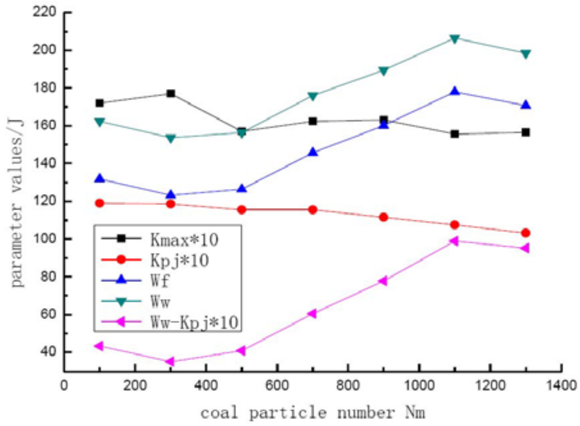
5.2. **Effects of coal size distribution.** Coal particles are of different sizes in the grinding process of a mill cylinder. To further simulate actual operation conditions of a ball mill, PFC3D experiments are respectively conducted on coal particles (3-8 mm) with a uniform distribution and a Gaussian distribution. In addition, the balls' strain energy is researched. Figure 5(a) shows the PFC3D motion of the coal particles with $N_m = 100$ with a uniform distribution corresponding to the balls of $D_b = 0.03$ m and $N_{0.03} = 200$, which reach their maximum kinetic energy when the mill is running in a steady state. Figure 5(c) shows the PFC3D motion of the coal particle Gaussian distribution with



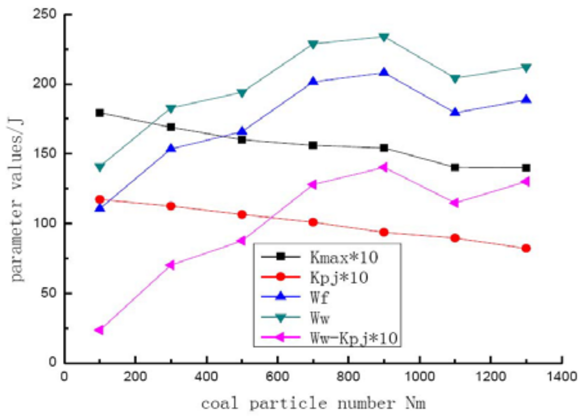
(a) $R_m = 3$ mm



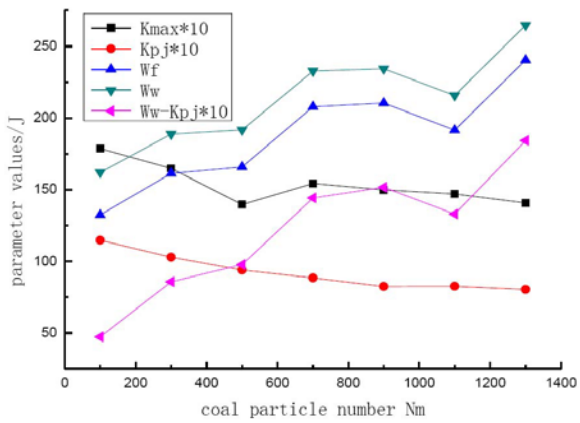
(b) $R_m = 4$ mm



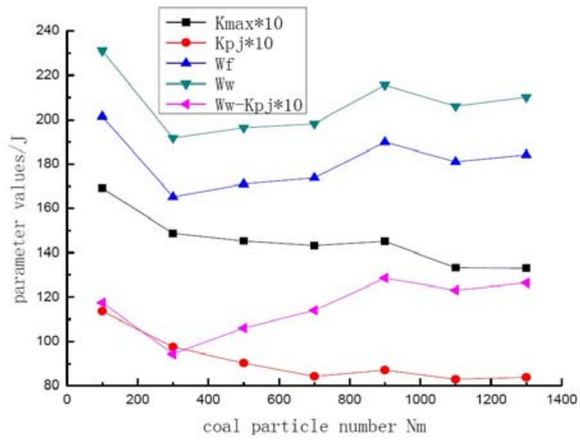
(c) $R_m = 5$ mm



(d) $R_m = 6$ mm



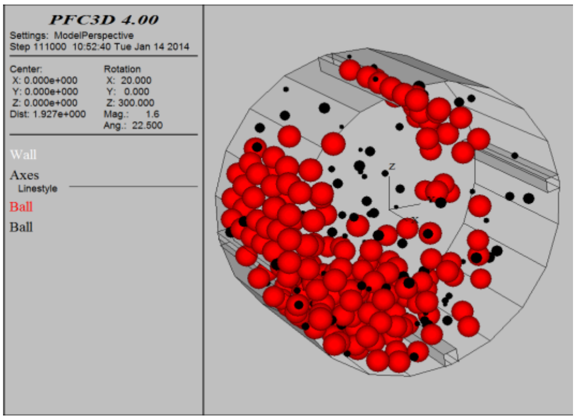
(e) $R_m = 7$ mm



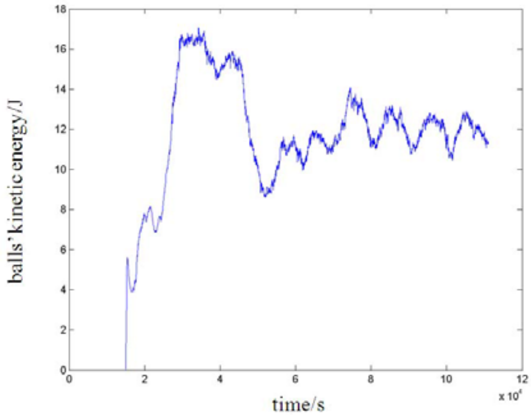
(f) $R_m = 8$ mm

FIGURE 4. Scatter diagram of balls' energy values of $D_b = 0.03$ m and $N_{0.03} = 200$ for coal particles with different diameters with increasing coal loads

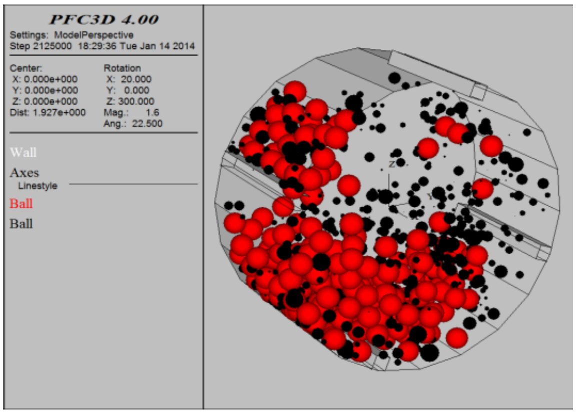
$N_m = 500$ under otherwise identical conditions. Figure 5(b) and Figure 5(d) demonstrate the real-time variation curve of the balls' kinetic energies in Figure 5(a) and Figure 5(c), respectively. Table 8 and Figure 6 show the maximum and average values of the balls' kinetic energy, the strain energy, the friction energy consumption and the mill's total work with increasing coal loads.



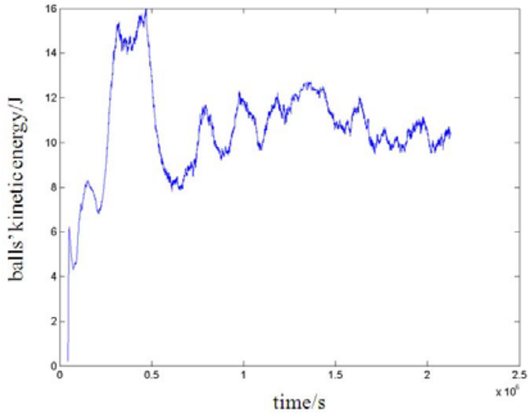
(a) Simulation model of ball motion with uniform distribution



(b) Real-time kinetic energy of balls with uniform distribution

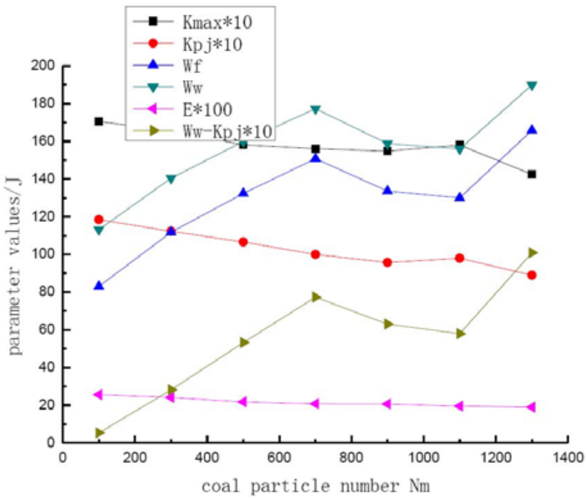


(c) Simulation model of ball motion with Gaussian distribution

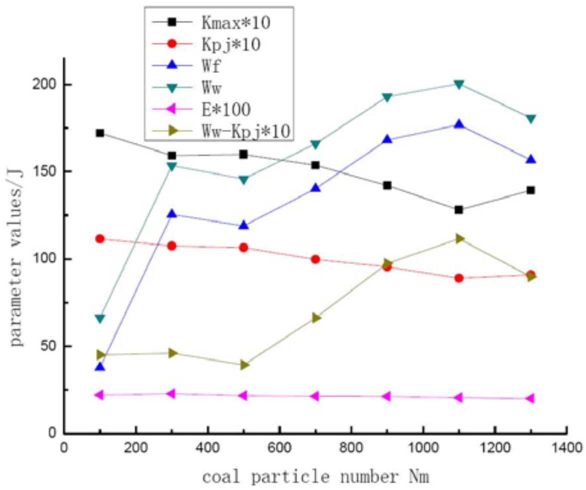


(d) Real-time kinetic energy of balls with Gaussian distribution

FIGURE 5. PFC3D effect chart of $D_b = 0.03$ m and $N_{0.03} = 200$



(a) Coal particle uniform distribution



(b) Coal particle Gaussian distribution

FIGURE 6. Scatter diagram of balls' energy values with different distributions with increasing coal loads

TABLE 7. Parameters of ball motion of $D_b = 0.03$ m and $N_{0.03} = 200$ for coal particles with different diameters with increasing coal loads

coal radius R_m/mm	coal particle number N_m	coal quality M_m/g	maximum of kinetic energy $K_{\max}$/J	average of kinetic energy K_{pj}/J	friction energy consumption W_f/J	the mill's total work W_w/J	$(K_{pj}/W_w - K_{pj0}/W_{w0})$ /%
–	0	0	17.9560	11.0815	61.8486	171.7084	0
3	100	8.4823	18.4200	11.8601	109.3896	139.5029	2.0480
	300	25.4470	17.7390	11.9217	98.6012	129.2631	2.7691
	500	42.4116	17.7110	12.2807	110.7425	142.0282	2.1930
	700	59.3762	17.9750	11.9508	98.0951	128.7367	2.8294
	900	76.3409	17.7510	12.2116	127.6370	158.8133	1.2356
	1100	93.3055	18.2700	11.8723	112.5965	142.8260	1.8587
	1300	110.2702	17.7050	12.0878	107.2337	138.3463	2.2836
4	100	20.1062	18.2910	11.9110	119.2798	149.7024	1.5028
	300	60.3187	17.3140	12.0441	109.8393	140.6787	2.1077
	500	100.5312	18.7540	11.9498	135.0337	165.7603	0.7554
	700	140.7437	17.7370	12.1595	143.8535	175.1578	0.4883
	900	180.9562	18.0130	12.0437	157.8658	188.9546	−0.0798
	1100	221.1686	16.6650	12.0839	170.0929	201.4641	−0.4557
	1300	261.3811	17.1420	11.8104	166.5611	197.3822	−0.4702
5	100	39.2700	17.1940	11.9048	131.7846	162.3577	0.8788
	300	117.8100	17.7010	11.8545	123.2225	153.6668	1.2607
	500	196.3500	15.7040	11.5505	126.3709	156.3924	0.9319
	700	274.8900	16.2320	11.5545	145.6957	176.0406	0.1098
	900	353.4300	16.3160	11.1580	160.1657	189.4296	−0.5634
	1100	431.9700	15.5670	10.7510	177.9508	206.4539	−1.2462
	1300	510.5100	15.6460	10.3241	170.7370	198.4179	−1.2505
6	100	67.8586	17.9300	11.7325	110.6703	140.9874	1.8680
	300	203.5757	16.8930	11.2513	153.5404	182.8044	−0.2989
	500	339.2928	16.0060	10.6435	165.8875	194.0834	−0.9697
	700	475.0099	15.6030	10.0926	201.5703	228.8249	−2.0431
	900	610.7270	15.4170	9.3746	208.1217	234.0111	−2.4477
	1100	746.4442	14.0340	8.9602	179.3081	204.3444	−2.0688
	1300	882.1613	14.0020	8.2211	188.5687	212.2476	−2.5803
7	100	107.7569	17.8610	11.4789	132.4131	162.1031	0.6275
	300	323.2706	16.4950	10.2926	161.3795	188.7441	−1.0005
	500	538.7844	13.9560	9.3920	165.8925	191.6467	−1.5530
	700	754.2982	15.4390	8.8469	207.8076	232.6820	−2.6516
	900	969.8119	14.9910	8.2572	210.3417	234.3235	−2.9299
	1100	1185.3257	14.7020	8.2780	191.5775	215.7608	−2.6170
	1300	1400.8394	14.0710	8.0506	240.4893	264.7485	−3.4129
8	100	160.8499	16.9070	11.3625	201.4036	231.0797	−1.5366
	300	482.5498	14.8800	9.7399	165.2077	191.6881	−1.3726
	500	804.2496	14.5300	9.0324	170.9975	196.3850	−1.8544
	700	1125.9494	14.3190	8.4223	173.7203	198.2341	−2.2050
	900	1447.6493	14.5090	8.7080	189.8600	215.6625	−2.4159
	1100	1769.3491	13.3320	8.2913	180.9980	206.0527	−2.4298
	1300	2091.0490	13.3020	8.3778	184.1712	210.1345	−2.4668

These results show that strain energy of the balls is much smaller than the balls' kinetic energy and the mill's total work. Consequently, the strain energy of the balls is amplified a hundred times to reflect the variation of the parameter values in the figure. Balls are less affected by the kinetic energy of the cylinder rotation movement. Assuming the dynamic and temperature effects are not considered in the process of deformation, the work performed by the mill's total work on the balls would be all stored in the coal in the form of strain and stress, and the work would be transformed into strain energy. The balls' energy is almost all utilized to impact and grind coal particles.

In Figure 3 and Figure 5, the balls and coal in the mill are going through a cascading motion, a projectile motion of several balls, and a projectile motion of most of the balls, respectively. Their kinetic energy gradually reaches its maximum. The projectile motion is a ball's optimal motion state, and it corresponds to the mill's highest grinding efficiency.

TABLE 8. Parameters of ball motion with coal particle size distribution with increasing coal loads

coal radius R_m/mm	coal particle number N_m	coal quality M_m/g	maximum of kinetic energy $K_{\max}$/J	average of kinetic energy K_{pj}/J	friction energy consumption W_f/J	the mill's total work W_w/J	strain energy E/J	$K_{pj}/W_w - K_{pj0}/W_{w0}$ /%
–	0	0	17.8830	11.4893	141.7186	172.8351	0.2601	0
3-8 uniform distribution	100	8.4823	17.0560	11.8477	82.9805	113.1157	0.2558	0.0382
	300	25.4470	16.5370	11.2257	111.8111	140.4990	0.2418	0.0134
	500	42.4116	15.8100	10.6638	132.3583	159.9086	0.2181	0.0002
	700	59.3762	15.6080	9.9978	150.7898	177.2566	0.2084	−0.0101
	900	76.3409	15.4840	9.5772	133.6082	158.7568	0.2073	−0.0062
	1100	93.3055	15.7940	9.7941	129.9792	155.9744	0.1953	−0.0037
	1300	110.2702	14.2520	8.9018	165.8037	189.9231	0.1897	−0.0196
3-8 Gaussian distribution	100	8.4823	17.2260	11.1446	37.9646	66.4125	0.2215	0.1013
	300	25.4470	15.9320	10.7486	125.5525	153.4860	0.2277	0.0035
	500	42.4116	15.9940	10.6574	118.9427	145.9220	0.2174	0.0065
	700	59.3762	15.3750	9.9808	140.3225	166.0947	0.2133	−0.0064
	900	76.3409	14.2150	9.5579	168.2991	193.0197	0.2120	−0.0170
	1100	93.3055	12.8150	8.8964	176.9418	200.5623	0.2049	−0.0221
	1300	110.2702	13.9430	9.0960	156.7883	180.7909	0.2003	−0.0162

In Table 7, when the coal particles' radius and coal load are proper, the average value of the balls' kinetic energy as a percentage of the mill's total work gradually increases and then decreases in comparison with the situation when there is no coal. In Figure 4 and Table 8, when the coal particle's radius is proper and the coal load increases, the difference between the mill's total work and balls' work on the coal experiences a minimum point and then increases. In addition, the use ratio of the balls' kinetic energy increases first and then decreases, and the mill's efficiency likewise increases first and then decreases. In the comparison between Table 8, Figure 6, Table 7, and Figure 4, we can learn that when the coal particles are governed by a uniform distribution or a Gaussian distribution, with the increasing coal loads, the increasing range of the energy consumption of the friction and the mill's total work is larger than for a situation with equal particle radiuses. The use ratio of the balls' kinetic energy similarly increases in the beginning and then decreases with increasing of coal loads. In conclusion, the balls' real-time kinetic energy can indicate the mill's coal load in a more precise way, and the mill obtains the optimal coal load when the balls reach a maximum kinetic energy, corresponding to the highest grinding efficiency. The energy consumption of the friction and the mill's total work further indicate the use ratio of the balls' impact force, thus demonstrating the mill's grinding efficiency in various ways.

5.3. **Correlative degree and balance degree method.** From the DEM simulation's results, analysis of the ball motion with increasing coal particles with different diameters clearly demonstrates that there exists a close relationship between the coal load and the balls' real-time kinetic energy in the operational process of a ball mill. According to the above study, a balanced adjacent degree between the coal load and the balls' kinetic energy is proposed.

The coal load in experimental data is selected as the reference data sequence, while other parameters, such as the balls' kinetic energy, the friction energy consumption and the mill's total work, are comparison data sequences. $B_{a1}(X_i, X_j)$ represents the balance degree between the coal load and other parameters when $D_b = 0.03$ m when the balls possess optimal projectile motion. $B_{a2}(X_i, X_j)$ represents the balance degree between the coal load and other parameters when $D_b = 0.04$ m and when the balls possess optimal projectile motion. The results in Table 9 show that every parameter's balanced adjacent

TABLE 9. Balanced adjacent degree of parameters and coal loads

balanced adjacent degree \ parameters	$K_{\max}$	K_{pj}	W_f	W_w
$B_{a1}(X_i, X_j)$	0.6920	0.6936	0.6926	0.6929
$B_{a2}(X_i, X_j)$	0.6946	0.6948	0.6916	0.6926

degree exceeds 0.6, and every parameter's sensitivity to the variation of the coal load is high. While the balanced adjacent degree between the balls' kinetic energy and the coal load is slightly higher than the friction energy consumption and the mill's total work, it could better explain the coal load and reflect the working efficiency.

6. Conclusions.

The balls' kinetic energy is utilized to detect and control the coal load. The relationship between the boiler operation parameters, the coal load and the balls' kinetic energy is analyzed carefully. Several important conclusions may be drawn.

1) The balls' kinetic energy is more associated with the coal load of ball mill than with the boiler operation parameters by a polynomial fitting and information fusion model.

2) Results of the DEM experiments show that projectile motion is the optimum state for the balls to obtain the maximum kinetic energy, and there is a corresponding optimum coal load at this moment. A close relationship between the coal load of ball mill and ball movement is found. It is further indicated that the balls' kinetic energy directly reflects the coal load by a balanced adjacent degree method.

3) In comparison with existing coal load control methods, this novel method (which is based on the balls' kinetic energy) decreases the influence of other environmental factors on coal detection and enhances the accuracy of coal load control.

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